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Structure, Intent & Conformance Monitoring in ATC

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Abstract: In field studies of current Air Traffic Control operations it is found that controllers rely on underlying airspace structure to reduce the complexity of the planning and conformance monitoring tasks. The structure appears to influence the controller's working mental model through abstractions that reduce the apparent cognitive complexity. These structure-based abstractions are useful for the controller's key tasks of planning, implementing, monitoring, and evaluating tactical situations. In addition, the structure-based abstractions appear to be important in the maintenance of Situation Awareness. The process of conformance monitoring is analyzed in more detail and an approach to conformance monitoring which utilizes both the structure-based abstractions and intent is presented.

1 Introduction

It is expected that Air Traffic Control (ATC) systems will continue to experience a growth in demand for services in the future, despite the challenges faced by the global aviation industry following the events of September 11, 2001. Proposals to increase capacity and efficiency to handle the anticipated growth are expected to require fundamental changes to ATC operations. In order to understand how such changes may impact safety, security and controller workload, the operations of the current system need to be well understood. In particular, the roles that structure and intent have on the apparent complexity and cognitive processes of air traffic controllers are key elements. A better understanding of the use of structure and the importance of intent information can be used to guide new operational concepts and airspace design.

2 Methodology

In order to investigate how structure is used in the current system, a series of site visits to ATC facilities in the United States and Canada have been conducted. Sites observed include: Boston, Newark and Manchester Towers; Boston, New York and Manchester TRACONs; Boston, Cleveland, New York and Montreal Enroute Centers; and the ATC System Command Center in Herndon, VA. The site visits consisted of focused interviews with controllers, traffic management unit and training personnel as well as observations of live operations. To gain additional insight into the use of structural factors identified during the site visits, current traffic patterns were analyzed using data derived from the Enhanced Traffic Management System

(ETMS) data-stream. In order to investigate uses of intent in the current system, Host computer system flight plan and radar track data were also analyzed.

3 ATC Process and Abstraction Model

3.1 ATC Process Model

A generalized model capturing the key processes of an individual air traffic controller identified in the field observations is presented in Figure 1. This conceptual model also describes some of the observed and hypothesized interactions between structure, structure-based abstractions, intent, and the cognitive processes of an air traffic controller. The total cognitive space of a controller will be very large, encompassing many concepts and processes that may have little or no bearing on the performance of the tasks related to providing air traffic control services. Thus, Figure 1 focuses on a small subset of an air traffic controller's cognitive space.

At the highest level, five key cognitive processes were identified as elements of the air traffic control task:

- Planning
- Implementing
- Monitoring
- Evaluating
- Maintenance of Situation Awareness

These observations are consistent with those identified by Pawlak [1]. Figure 1 shows their hypothesized relationship to Situation Awareness, defined by Endsley as: "the perception of elements in the environment, within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [2]. In the model, a controller's Situation Awareness influences the decision processes, including planning, monitoring and evaluating.

The "Current Plan" is the controller's internal representation of the schedule of events and commands to be implemented as well as the resulting aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner.[1] As shown in Figure 1, the "Current Plan", along with the results of the decision process, is used to implement a set of commands that act on the air traffic situation. Through a surveillance path, the impact of those commands on the Air Traffic Situation is fed back to the controller's Situation Awareness. The monitoring process observes the air traffic situation to ensure that the individual aircraft are conforming to the "Current Plan". The "Current Plan" is constantly evaluated to ensure its effectiveness in producing conflict-free, efficient trajectories. The outputs from both the monitoring and evaluation functions can trigger a re-plan process if required.

[1] Note that "conflict" is used in the most general sense and could include aircraft-weather, aircraft-airspace and traffic management flow restriction conflicts, in addition to the traditional sense of aircraft-aircraft conflicts.

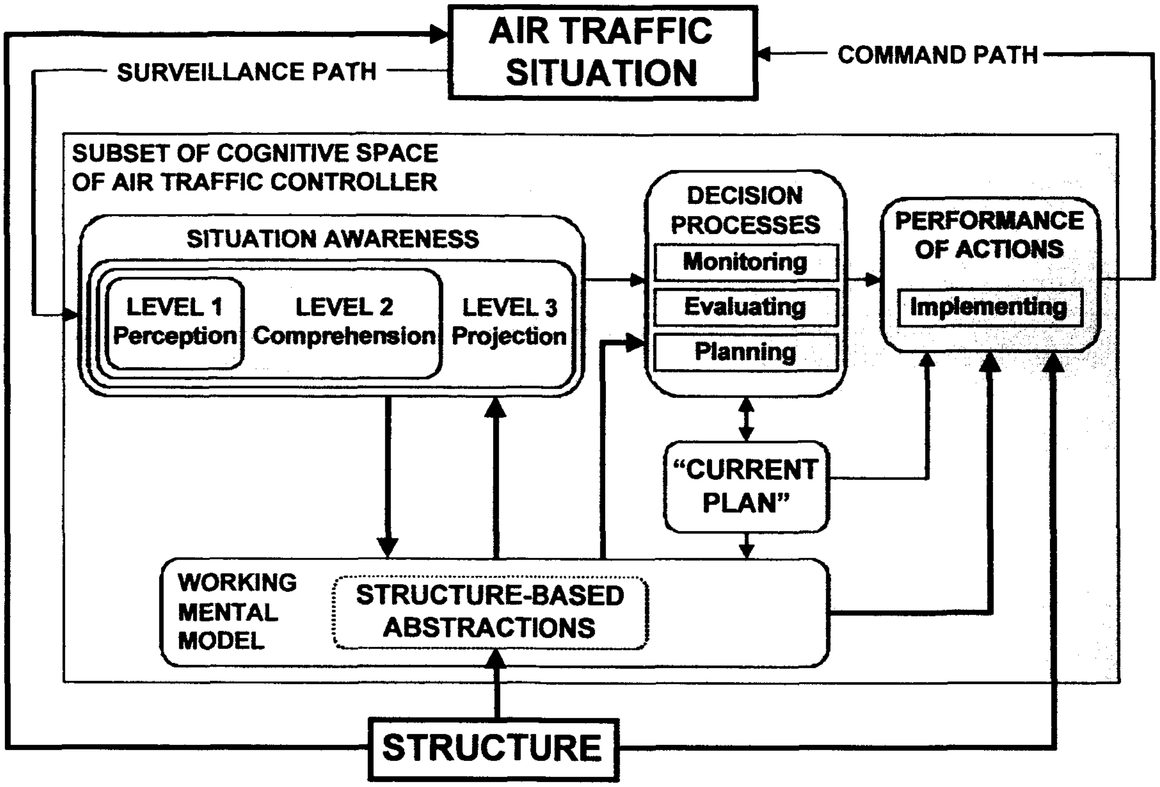

Figure 1: Generalized model of a subset of the cognitive space of an air traffic controller (adapted from Endsley [2])

3.2 Mental Models and Abstractions

Structure appears to influence the decision processes and the controller's Situation Awareness by forming the basis for abstractions that simplify a controller's working mental model. As shown in Figure 1, a working mental model supports the generation and maintenance of Situation Awareness as well as the various decision making and implementation processes. Mogford [3] has argued that a mental model is comprised of the mechanisms used to generate the content that comprises a controller's Situation Awareness. For example, a predicted trajectory may be a cognitive entity corresponding to Level 3 Situation Awareness, but the act of generating that trajectory can be associated with the current working mental model. It is hypothesized that there is a dual interaction whereby the working mental model provides mechanisms by which projections can be made while the data used to feed those mechanisms is supplied by the controller's Situation Awareness.

The working mental model is thought to be constructed, in part, of abstractions which are simplified versions of the system dynamics. Abstractions are a means of representing the essential characteristics of a mental model in a more cognitively compact form that is manageable within the constraints of human memory and processing limitations. Rasmussen [4] states that abstraction is "not merely removal of details of information on physical or material properties. More fundamentally, information is added on higher level principles governing the cofunction of the various functions or elements at the lower levels."

A notional representation of the abstraction process is presented in Figure 2. Before abstraction, limited attention resources allow consideration of only part of the mental model (e.g. that information included within the "attention spotlight"). After using an abstraction to simplify part of the mental model (the multiple grey boxes become one black box in Figure 2), the human is able to attend to a simplified version of the entire system in his or her mental model.

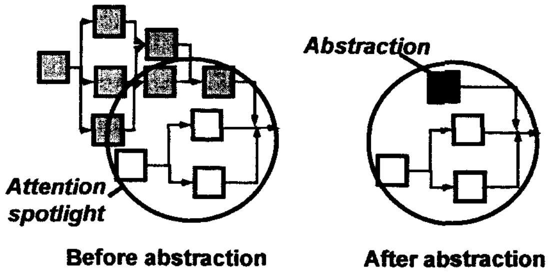

Figure 2: Illustration of the process of abstraction

Based on the field observations, it appears that structure forms the basis for several key abstractions used by controllers. Structure constrains the potential paths along which an air traffic situation may evolve (e.g. standard operating procedures may define handoff points). Knowledge of this structure allows for abstractions that simplify a controller's dynamical model of the evolution of an air traffic situation.

4 Examples of Structure-Based Abstractions

In the field observations, three key structure-based abstractions were identified [5]. The key abstractions identified are Standard Flows, Groupings and Critical Points, as summarized briefly below.

4.1 Standard Flows

The standard flow abstraction emerges as a means of classifying aircraft into standard and non-standard classes on the basis of their membership in established flow patterns in a sector (see Figures 3 and 4). An aircraft identified as a member of a standard flow carries with it an associated set of higher-level attributes such as expected future routing, ingress and egress points from the airspace, and locations of probable encounters. These attributes form a generalized expectation of an aircraft's trajectory through the airspace. In contrast, aircraft that are operating in ways that do not fall into the normal operating pattern, such as the "non-standard" aircraft in Figure 3, do not provide the same simplifications.

4.2 Groupings

A second abstraction identified was the grouping of aircraft linked by common properties. An example of such a basis is the standard flight levels associated with particular directions of travel. Such a basis potentially allows controllers to project and manage flight levels independently by taking advantage of the presumed non or minimal interaction between aircraft in each group.

The grouping abstraction can also operate on the basis of the simple proximity of aircraft, as shown in Figure 3. In this case, the use of a grouping abstraction can act to simplify the output from a controller, i.e. the execution of the results of the decision process. This may occur when several aircraft are given identical clearances or multiple aircraft divert around convective weather.

4.3 Critical Points

Critical points in the airspace were also identified as an example of a structure-based abstraction. The underlying structure (in the form of crossing and merge points of flows) will tend to concentrate the occurrences of encounters at common locations, also illustrated in Figure 3. Focusing on the intersection points of aircraft flows reduces the need for controllers to evaluate the potential for conflict over all possible pairs of aircraft within those flows [1]. The interaction between two aircraft approaching a merge point reduces a four-dimensional conflict to a one- or two-dimensional phasing problem. The same encounter geometry in the absence of a known critical point abstraction may require consideration of multiple dimensions, making the projection task more difficult. Figure 4 shows the arrival flows into Chicago's O'Hare airport and illustrates several examples of standard flows and localized critical points in the form of merges in the arrival stream.

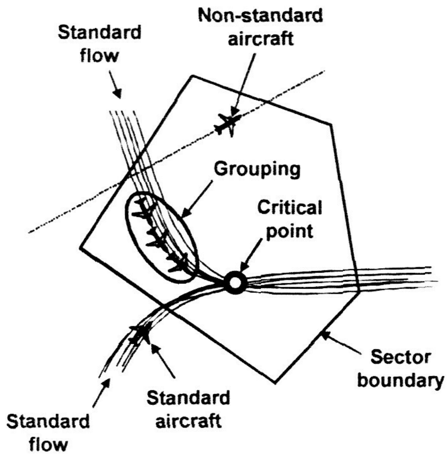

Figure 3: Illustration of structure-based abstractions: standard flows, groupings and critical points

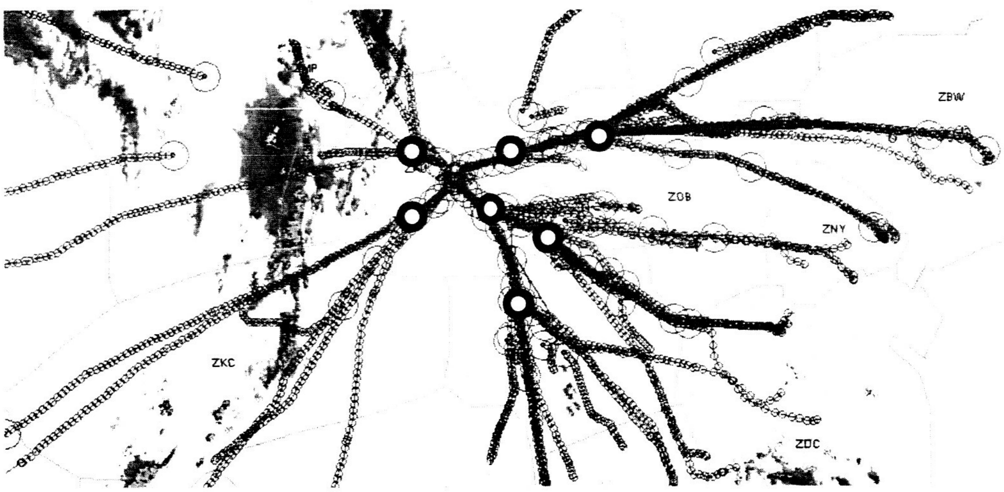

Figure 4: Examples of critical points in standard flows into Chicago O'Hare airport represented by white dots (21:00 EDT, May 3, 2001)

5 Conformance Monitoring & Intent

The monitoring process has been identified above as a core task of the air traffic controller. A subset of the general monitoring process is the conformance monitoring function [2] required to determine whether aircraft are adhering to the trajectories implied by the "Current Plan". Knowledge of an aircraft's conformance status is important for safety and efficiency reasons as non-conformance indicates a deviation from expected traffic patterns, which requires re-evaluation of the "Current Plan" for the sector. The importance of the conformance status of aircraft has also emerged as a security issue following the events of September 11, 2001. The conformance monitoring process is used as an example to more deeply consider the cognitive processes relating structure and intent.

5.1 Modelling Controller Conformance Monitoring

A proposed representation of the current conformance monitoring processes for a tactical air traffic controller is presented in Figure 5. The conformance monitoring process begins with the controller determining and communicating their intent for each aircraft to execute the "Current Plan" for the traffic in their sector. In this context, intent is defined as "the future actions of an aircraft that can be formally articulated and measured in the current ATC/flight automation system communication structure" [6] and represented as a state vector, ***I(t)*** defined by:

$$\boldsymbol{I(t)} = \left\{ \begin{array}{c} \textbf{\textit{Current target states, C(t)}} \\ \textbf{\textit{Planned trajectory, T(t)}} \\ \textbf{\textit{Destination, D(t)}} \end{array} \right\}$$

The controller's intent for a specific aircraft manifests itself as the clearance that is communicated to each aircraft. The currently-active set of clearances imply a "conformance basis" which is the observable manifestation of the controller's "Current Plan" and provide a baseline against which the conformance of an aircraft is determined. Consistent with the definition of intent, the clearances and conformance bases can exist at various levels including the target state level (e.g. assigned heading, altitude, speed); trajectory level (e.g. Flight Plan, standard flow) or some less structured level (e.g. descend at pilot's discretion).

In Figure 5, the conformance monitoring function is represented at the upper right of the controller block. It determines whether the behavior of an aircraft observed through surveillance systems (including the controller's perception and attention channels) is consistent with their expectation given the conformance basis. The conformance basis is transformed into these expected states through the controller's mental model which is compared to the observed states surveilled from the "real world".

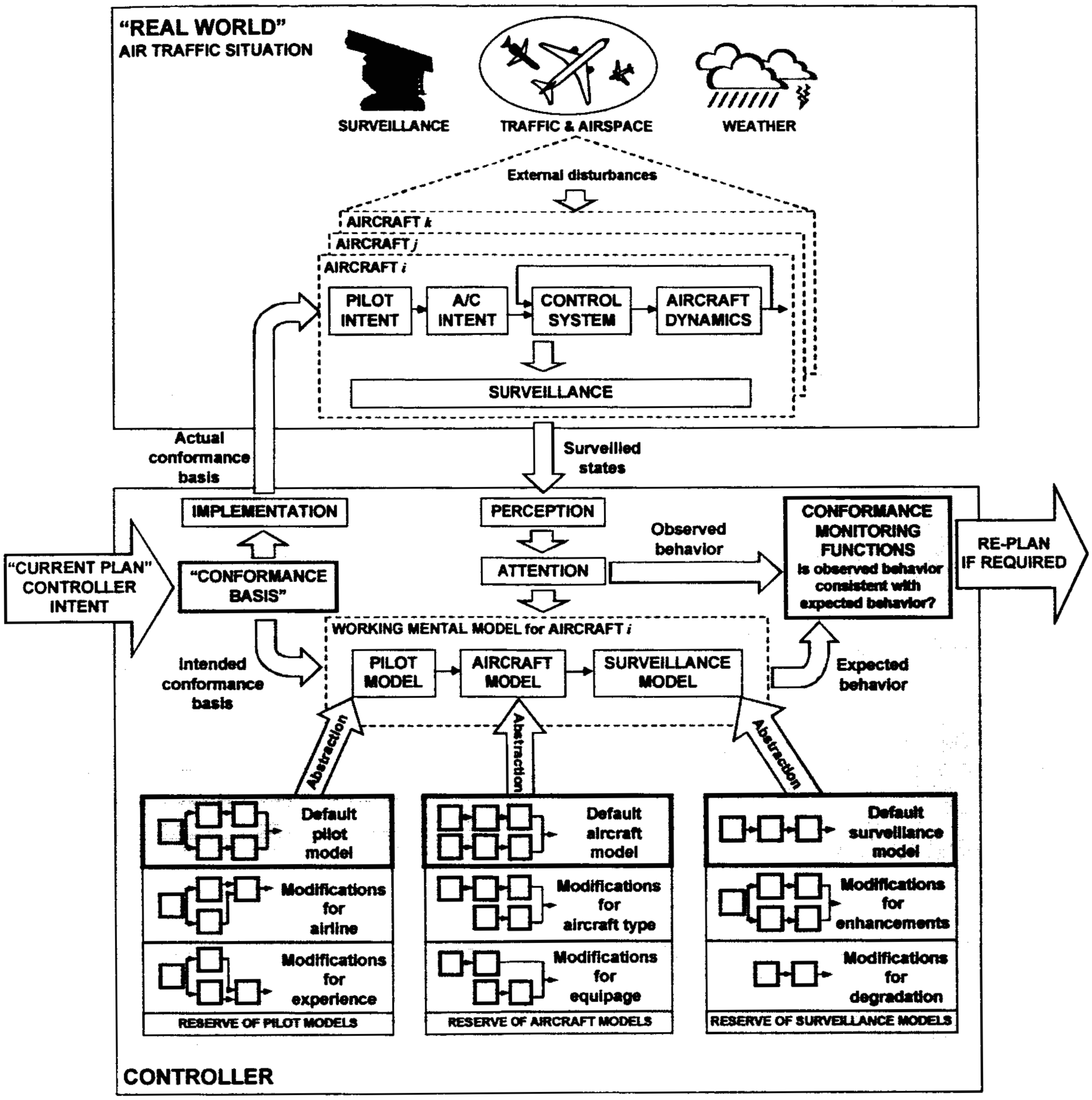

Figure 5: Example of controller conformance monitoring processes

The important elements required to define the behavior of each aircraft in the "real world" are represented by the dashed boxes in the upper portion of Figure 5. A classical feedback control representation of the aircraft control system and dynamics is used, but this is supplemented with upstream pilot and aircraft intent components that generate the control system target states [6]. Given the conformance basis from the controller, the "pilot intent" block represents the pilot's internal plans for the aircraft, which (in advanced aircraft) can be communicated to the autoflight system at both trajectory and target state levels through the FMS Control Display Unit and/or autopilot Mode Control Panel respectively. The "aircraft intent" component represents the intent resident in the aircraft's autoflight system which can be thought of as the programmed trajectory that would be executed by the aircraft if the automation was engaged. The aircraft flight control system takes the target states from the aircraft automation and sends commands to the aircraft flight control surfaces and other controls, which modify the trajectory through the aircraft's dynamic properties. The dynamic states of the aircraft and any disturbances (e.g. winds) are fed back to the control system to manage the trajectory to the appropriate target states.

The surveillance systems (e.g. radars) provide input through the controller's perception and attention channels. This provides both the observed state behavior to the controller's internal conformance monitoring function and also aids in the construction of the working mental model, which transforms the intended conformance basis to an expectation of aircraft behavior (in terms of expected trajectories). The working mental model is represented at a higher level of abstraction than the real world processes consistent with controller abstractions and heuristics identified in the controller interviews and field observations. In this example representation, the working mental model contains sub-models of the pilot, aircraft and surveillance components, which are populated through appropriate abstractions. It is assumed that there is a default abstraction for each of the key components in the mental model. These default abstractions can be supplemented by more situation-specific models from a reserve of standard abstractions or can be synthesized in real time for non-standard cases. The default abstractions and model reserves are thought to be developed through training and operational experience, as suggested by the field studies and the analysis of Host computer system/radar track data. For example, Figure 6 presents examples of cross-track deviation data (i.e. deviation of the radar data from straight-line segments drawn between waypoints in the active flight plan) for two aircraft types with different navigational capabilities. Observations of such behavior over time could be a basis for the development of controller abstractions for different aircraft types and equipages.

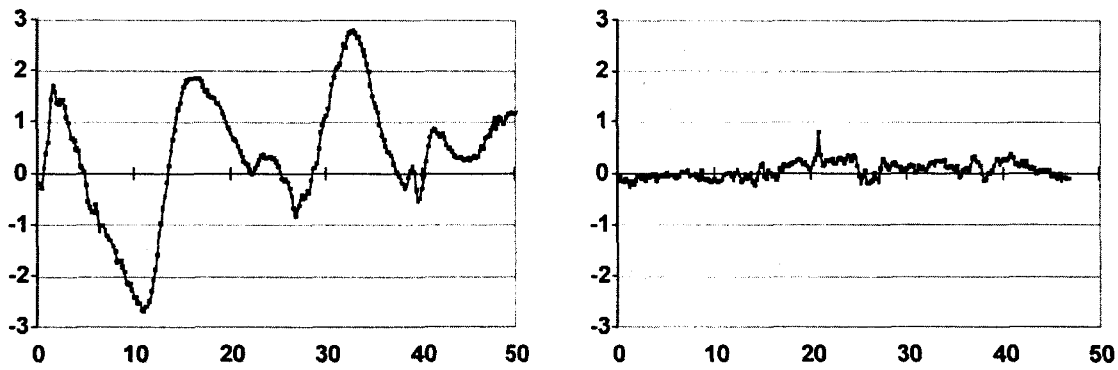

Figure 6: Example cross-track deviation data for VOR/DME-equipped B737 (left) and FMS-equipped A320 (right)

5.2 Automated Conformance Monitoring

The general framework outlined in Figure 5 can also form the basis for automated systems to support the conformance monitoring task. This approach is represented in Figure 7 where the controller's working mental model is replaced by an explicit "conformance monitoring model" which has contents that directly mirror the components that define the aircraft's behavior in the real world. The set of states that could potentially be surveilled are shown by the downward arrows in the figure. When available, these surveilled states aid in the population of the appropriate conformance monitoring model element, resulting in a higher fidelity model relative to when these states are not available (requiring the model be populated based on assumptions).

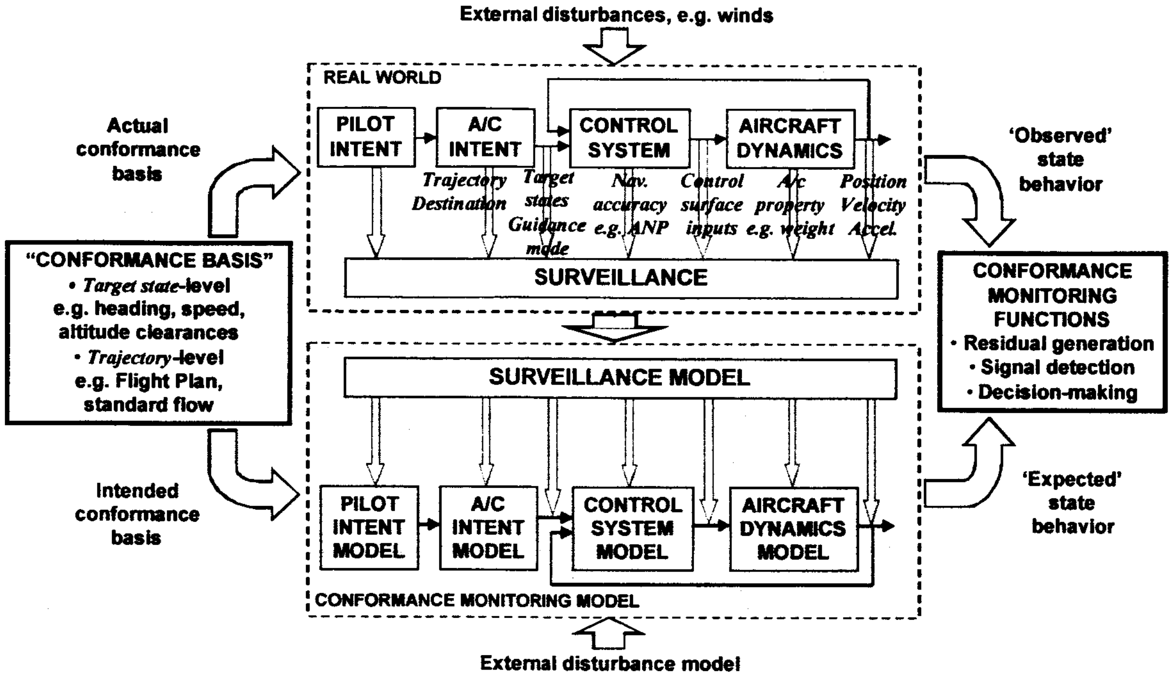

Figure 7: Framework for automated conformance monitoring system development

The conformance monitoring model generates expected state behaviors which are compared with the observed state behaviors in the conformance monitoring function. The conformance monitoring representation shown in Figure 7 is directly analogous to classic fault detection approaches, implying that fault detection methods (e.g. residual generation, signal detection and decision-making [7]) can be used to detect non-conformance. In addition, once non-conformance has been detected, fault isolation techniques can be employed to help perform "intent inferencing", (i.e. inferring what the aircraft *is* doing if it *is not* following the assumed conformance basis) which helps in any re-planning effort. In intent inferencing, the conformance monitoring model is run using alternate conformance bases or model parameters (e.g. to represent different operating modes) until the difference between the observed behavior and the new expectation is minimized. Even if the real behavior cannot be accurately determined, this approach enables certain behaviors to be excluded or ranges of possible behaviors to be identified to aid the re-planning task in the face of non-conformance.

Since the state information available in the environment determines the fidelity of both the observed aircraft behavior and the level of refinement in the conformance monitoring model, the effect of different surveillance environments on the conformance monitoring process can be investigated. This approach is being used to investigate datalink requirements (e.g. ADS-B message contents) for effective conformance monitoring and to study what new operating paradigms such technologies could enable.

6 Summary

Field studies of current operations have been used to investigate the use of structure in Air Traffic Control. Based on these observations, a model of key ATC processes and controller congitive abstraction has been developed. In the model, it is asserted that controllers rely on underlying airspace structure and procedures to support Situation Awareness and to reduce the complexity of the planning and conformance monitoring tasks. The modeling approach was further developed for the task of conformance monitoring. From this model an approach to conformance monitoring and intent inferencing has been proposed based on an intent state vector framework and analogies to fault detection and isolation. The formal representations of the use of structure and intent information can be used to guide changes to the current operational paradigms.

Acknowledgements

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